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SUBSONIC CHOKED FLOW LDV CALIBRATOR/VELOCITY STANDARD DEVELOPMENT

Peter M. Sherrouse

Calspan Corporation

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Marshall K Kingery

MARSHALL K. KINGERY
Facility Technology Division
Directorate of Technology
Deputy for Operations

Approved for publication:

FOR THE COMMANDER

M L Laster

MARION L. LASTER
Director of Technology
Deputy for Operations

SUMMARY

In an LDV entry in the AEDC 1-Ft Transonic Wind Tunnel where harsh environmental conditions exist; e.g., high temperature, vibration, etc., an asymptotic drift in measured flow velocity of a few percent was noticed following startup each day. To resolve the issue of whether the tunnel or the LDV was responsible and to aid in the correction of the problem, a device was developed which produces invariant particle velocities for use as a velocity standard in the tunnel environment. The development of such a device is herein discussed. The analysis demonstrates the device to be satisfactory for resolution of the "startup drift" problem and, with some additional development, could be used in checkout and calibration of an LDV.

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1.0 INTRODUCTION

The work reported herein was performed at the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F, Control Number 9R02, at the request of the Directorate of Technology (DOT), AEDC. The Air Force project manager was Mr. M. K. Kingery, AEDC/DOF. The results were obtained by the Calspan Corporation/AEDC Division, operating contractor for the Aerospace Flight Dynamics testing effort at AEDC, Arnold Air Force Station, TN, under AEDC Project Number DB09VW (Calspan No. V35N-CL).

Laser Doppler Velocimeter (LDV) (Ref. 1) installations in the 1-Foot Transonic Tunnel (1T) required exposure of the optical system to harsh environmental conditions; e.g., high temperature, temperature gradients, acoustic vibration, etc. It was noticed during these installations that the measured free-stream velocity drifted asymptotically a few percent before stabilizing following tunnel startup each day. The mechanism which generates this "startup drift" was not understood nor was it clear whether the tunnel or the LDV system was responsible. In order to isolate the cause, a device was needed which could produce a fixed or near-fixed particle velocity which would be unaffected by its surrounding conditions. An LDV, while subjected to the harsh 1T environment, making reference measurements of such a fixed velocity, would indicate the responsible system (tunnel or LDV). Should the LDV be identified as responsible, such a device would assist in isolation and correction of the cause. In addition, if the device's flow angle were precisely adjustable and if the time and condition invariant velocity were absolutely known, it could also be used to calibrate and check the calibration of an LDV system.

A Laser Doppler Velocimeter is a device which generates two beams of laser light and causes them to cross at a specific point in a flow field under investigation. At the point where these beams cross, the light interacts with itself generating an interference pattern. As a particle entrained in the flow crosses this interference pattern, it alternately scatters and fails to scatter light. The frequency of this alternation is proportional to velocity.

Inaccurate velocity measurements stem mainly from two abnormalities in an LDV optical system. The first is a deviation from design in the angle between the plane containing the two crossing beams and the flow axis (beam-cross-plane angle). This causes the LDV to measure an incorrect flow velocity component as the LDV measures the component of velocity in the plane of, and perpendicular to the bisector of, the two beams. The second is error in the angle at which the beams cross. This has a direct bearing on the calibration of the LDV. The measured velocity (V_m) of a single component of an LDV is given by (Ref. 2):

$$V_m = [\lambda(2 \sin \theta/2)] \, (f_m - f_c) \qquad (1)$$

where λ is the wavelength of light, θ is the angle between the two beams, f_s is the signal frequency, and f_c is the carrier frequency (zero if no carrier is used). It's apparent that an error in θ causes V_m to be in error.

Current methods for measuring the angle between the beams have an inherent resolution of about 1 percent. Generally, these methods a) require shutting down the tunnel for their accomplishment; b) induce condition changes because of the time they require; and c) are difficult to reliably implement in the tunnel/test environment. As a result, the miniscule variation, should it even exist, that might be responsible for the warmup drift has avoided detection.

1.1 DESIGN CONSIDERATIONS

Several design considerations and operational characteristics were agreed upon by LDV and tunnel engineers. The output of a calibrator must be or simulate particles traveling at a well defined velocity and trajectory. Optical access must be provided to the measurement point. In that it is desirable to place the device inside an operating tunnel plenum for online checks, remote operation capability, immunity to surrounding conditions, insensitivity to measurement-position error, compact design, and ease of optical access are required. Other desirable features include: minimal calibration and maintenance, and the lack of required special support (nonroutinely available sources of compressed air, electrical power, etc.).

The most important of the operational characteristics mentioned are those dealing with velocity and trajectory angle. The proposed device must have an inherent repeatability better than that expected of the LDV system and if it is to be used to calibrate, the absolute velocity must be known to within the tolerance expected of the calibration itself. Also, the characteristic velocity of a satisfactory device must be higher than a required minimum. The minimum velocity criterion stems from the manner in which the LDV measures velocity. In a typical LDV system utilizing a carrier frequency to resolve flow direction, the signal processors have a resolution of at least 1 fps; therefore, to insure that a measurement would be accurate to within 1 percent, a flow velocity of at least 100 fps would be necessary. Any greater velocity, however, would be beneficial as long as confidence in the stability of the velocity magnitude itself remains high.

If, as envisioned, this device were to be placed in the plenum of 1T and used during testing for online checks, the maximum dimensions it could have would be 10 in. high by 12 in. wide by 24 in. long, with as little structure above the measurement point as possible. A smaller size would, of course, be welcome as the next requirement may not be as generous.

1.2 PROPOSED TECHNIQUES

Three proposed techniques were considered. These were: 1) A rotating glass wheel containing imbedded scatter particles, 2) a supersonic jet with entrained particles, and 3) a subsonic jet again with entrained particles.

1.2.1 Glass Wheel

The wheel as perceived was to be constructed of two glass optical flats sandwiched and glued with an index matching glue containing a suspension of particles of a desired size. With the index matching glue in the center, only the front and back surfaces would scatter light. The use of sufficiently thick optical flats would remove these surfaces far enough from the particles to allow the LDV to spatially filter light that might be scattered by them. By driving the wheel with a feedback controlled motor, rpm fluctuation could be reduced as opposed to a free-running drive mechanism. If a fixed rotational rate could be attained, the particles at a given distance from the axis would travel at a fixed velocity. An LDV system fixed on a point some distance from the axis would "see" the same series of particles repeatedly. This, incidentally, can be desirable. Coupled with an adjustable angular position trigger, the ability to observe a particle and its associated signal many times would exist, giving insight into the variability in the treatment of the same signal. This is otherwise difficult to discern. Although these desirable traits exist, several undesirable traits also exist. Each particle in such a wheel would have a different distance from the center and would therefore have a slightly different velocity. If, for instance, a 4-in. wheel were constructed and an LDV system with a typical probe volume diameter of 400 μm were used to measure velocity, particles in the 400-μm band 2 inches from the center would have velocities which vary by as much as 1 percent. Of course, as the wheel is increased in size this variation decreases; however, compactness is sacrificed. Another problem is the position-velocity sensitivity a wheel would have. If a wheel device were used in a tunnel situation and the LDV were returned to it from time to time, a reposition error would induce a change in measured velocity, trajectory angle, or both. In a similar manner as in the last example, a 400-μm position error on a 4-in. wheel would give a change of approximately 1 percent. Yet another pitfall would be the maximum velocity limitation. Because of centrifugally induced stress in the glass, the maximum particle velocities attainable would be less than 100 fps. From a developmental standpoint, the sandwich construction of the wheel presents many problems as does the rate-controlled drive mechanism. Although several experiments have been conducted in the lab involving particle-filled glass sandwiches, the ability to monodisperse 1-μm to 5-μm particles in glue (free of bubbles) in a desirable concentration does not as yet exist and would carry a substantial developmental risk factor. Although no monumental development problems are thought to exist in the drive/trigger mechanism and electronics, a sizeable effort may be involved.

1.2.2 Supersonic Nozzle

Examination of the supersonic nozzle flow concept showed it could yield desirably higher particle velocities and, with proper design, could possess a narrow trajectory angle distribution. Operation in the underexpanded mode would make the flow immune to surrounding (plenum) conditions, and would allow measurements just downstream of the exit (making windows unnecessary). Due to the high velocities and associated accelerations, however, particles would tend to lag the flow to varying degrees, depending on particle size and lag relaxation distance provided. Another drawback would be that upstream conditions (temperature and pressure) would affect flow conditions and therefore particle velocities. The most serious problems, however, are: 1) That in producing the critical throat contours in such a small scale, errors producing nonuniform flow would be difficult to avoid, and; 2) air supply pressure required for such a device would not be generally available at most locations of operation.

1.2.3 Subsonic Nozzle

A subsonic nozzle exhausting directly into free air or a tunnel plenum would produce quite sufficient velocities (up to 600 fps). Accelerations in a compact device could be low enough to allow lag relaxation and readily available shop air supplies could be used to power it. Subsonic nozzle contours would be much less critical than the supersonic counterpart and, correctly applied, confinement of velocity and trajectory angle distribution would be sufficient. Also position-velocity sensitivity would be negligible. Among these favorable characteristics one serious drawback existed. Upstream and downstream pressure changes would affect velocity. However, with a choke nozzle run critically (M = 1) downstream, partial independence can be obtained, making velocity (V) a function of temperature alone as described in the following relation (Ref. 3):

$$V = (K\ R\ T)^{1/2}\ (M) \qquad (2)$$

where T is temperature, M is the nozzle-to-choke Mach number ratio, and K and R are gas constants.

Both the supersonic and the choked flow subsonic nozzles are constant Mach number devices. With upstream temperature control, however, either would produce a repeatable velocity.

2.0 SUBSONIC CHOKED-FLOW NOZZLE DEVELOPMENT

Comparison of the proposed techniques indicated the choked-flow subsonic nozzle concept to be both viable and the most promising of the three.

Several considerations came to light with regard to the subsonic choked-flow concept.

1. Because the mass flow rate is controlled by a downstream choke, the test region could not be open but required a chamber with windows.

2. Although flow temperature would affect velocity, this effect could be compensated for by monitoring the temperature and recalculating velocity. Therefore, evaluation of the Mach number stability is sufficient and would make a complex temperature control system unnecessary.

3. Flow conditioning must precede the subsonic nozzle in order to remove turbulence and to control pressure and monitor temperature.

In light of these and other considerations, a Mach number of 0.5 was selected for the jet. This would give a quite sufficient theoretical velocity of 551 fps (standard room temperature and pressure). The subsonic jet-to-choke throat area ratio (A/A^*) which correlates with the Mach number selected is 1.3398. Laboratory experiments demonstrated that a 0.5-in. shop air supply would support choked flow in a 0.1875-in. diameter choke nozzle. A subsonic nozzle throat diameter of 0.2170 in. was then dictated by the area ratio. This size appeared to be quite satisfactory.

2.1 DESIGN

Figure 1 shows the result of the design effort. Flow enters on the left and is rapidly expanded and passed through the screens to ensure that no high velocity core exists and to break up any large scale turbulence in general. The flow then enters the settling chamber where temperature and pressure are monitored, small-scale turbulence is allowed to dissipate, and, should it be desirable to do so, seed is administered through a provided port. The subsonic nozzle then accelerates the flow rapidly, to prevent boundary layer buildup, and then maintains that velocity for a short distance to allow particles to accelerate to flow velocity. From here the flow enters the test chamber where an LDV would measure particle velocities by way of the windows provided. After this, flow is exhausted from the test chamber through the choke nozzle. Figure 2 shows the device as constructed.

A Druck 0- to 100-psi pressure transducer and a iron-constantan thermocouple with digital readouts were added to accurately monitor stilling chamber pressure and temperature, respectively. A bubble level to give an external reference of the flow axis and a thin glass target to aid in alignment of the LDV (object below nozzle in Fig. 2) were also added.

2.2 PERFORMANCE TESTING

Preliminary testing revealed that a stilling chamber pressure of 18 psig was required to drive the choke critical (required for operation). This was determined by a shadowgraph technique (Fig. 3). Evidence of underexpanded flow shock structure first became visible at 18 psid. These preliminary tests also indicated that the flow expander and screens were effective in core breaking and producing a uniform velocity across the diameter of the settling chamber.

2.2.1 **LDV Measurements**

An LDV system was employed (Fig. 4) in order to determine 1) whether significant particle lag existed; 2) whether the particle trajectories were uniform; and 3) to establish the size of the usable flow field area. The system used was a three-component (although only two components were used), forward scatter LDV system utilizing color separation to differentiate components. The velocity components, orthogonal to each other, were measured at plus and minus 45 deg from the tunnel axis and were mathematically rotated to yield the tunnel coordinate velocity components. The LDV system, mounted on a three-axis traverse, was moved to scan the flow field. Artificial seeding of the flow was not implemented as sufficient entrained dust existed in the shop air supply.

The coordinate convention adopted was the standard right-handed system with the X axis positive downstream and the Z axis positive up. The centerline of the flow was determined by scanning with the LDV just downstream of the nozzle exit, to find the jet boundaries.

As seen in Fig. 5, velocity data points 1-9 were taken at various positions in the flow in order to define the usable core region. Data points 10-15 were taken at the same central location as data point 5, however, with changes in supply pressure and/or temperature to observe their effect on the flow Mach number.

3.0 RESULTS

Because the desired output of the device is a known velocity and not necessarily an absolute velocity and because the velocity will be known as long as the flow temperature and nozzle Mach number are known, variations in Mach number due to condition changes are of concern. Therefore to facilitate evaluation, the Mach number was calculated for the velocity data taken. An average of data points 1-9 was determined and established as a reference Mach number. The percent deviation from this average was calculated for data points 1-9 individually as well as for points 10-15 where supply temperature and pressure were varied. These percent deviations are listed in Table 1 along with the apparent flow angle of each, computed from the measured velocity components.

Although the temperature and pressure variations are more than an order of magnitude greater than would be expected in normal operation, the "percent deviation in Mach number" column of Table 1 shows that in only one case did the deviation approach 1 percent. If restricted to data points where pressure and temperature are nominally the same; that is, those from which the average was taken (Nos. 1 to 9), then the deviation is typically 0.1 percent or less, and further, if confined to a smaller region of the flow (Nos. 1, 2, 4, 5, 7, 8, for instance), then the deviation may be significantly better than 0.1 percent. This is well within the established criteria.

The standard deviation in flow angle was computed for the similar pressure and temperature points and found to be 0.85 deg, which is acceptable for axial flow calibrations. However, the standard deviation for the region of the flow defined by data points 1, 2, 4, 5, 7, and 8 is 0.1 deg which is well within the predefined 0.5 deg criterion for cross-flow calibration. The dimensions of the smaller region defined by data points 1, 2, 4, 5, 7, and 8 are significantly larger than the reposition accuracy of the LDV system. Therefore the region is large enough to define the subsonic jet as position-velocity insensitive.

3.1 ADDITIONAL OBSERVATIONS

Having demonstrated the subsonic choked-flow nozzle exceeds the performance criteria in all required areas, two additional observations can be made from the data. First, the Mach number calculated from the measured flow velocities differs somewhat from the Mach number calculated from the nozzle area ratios. This difference is due to boundary layer development in the nozzles which make their effective areas somewhat less than the actual and to total pressure losses resulting from nonisentropic processes. This difference, however, is unimportant as long as the effective Mach number of the flow can be determined experimentally. Although the velocities measured are repeatable, it is not to be assumed that they are absolute nor were they intended to be. In order to determine the actual effective Mach number a more precise measurement (in terms of absolute velocity) will need to be taken. This can be accomplished with a special velocimeter setup in the laboratory where ardent attention is given to determining the angle between the beams and where processing electronics are verified for each velocity measurement.

Secondly, the ostensible flow angle apparent in the data and visible in Fig. 5 is attributable to one, or a combination, of the following: a) LDV-to-nozzle misalignment; b) beam-cross-plane to tunnel axis angle error in one or both components; or c) error in the angle between the beams in one or both components. In this application whether there existed an apparent flow angle or not was of little concern; consequently, the time required to assure its prevention was foreshortened. In a tunnel/test situation, however, this flow angle bias would be quite objectionable. If the ability to change and precisely set the X axis inclination of the jet existed and if the Mach number of the nozzle were characterized by determination of the absolute velocity, it would be a simple task to: 1) determine a bias existed, 2) determine the cause, 3) correct the cause. Such a capability would also make thorough day-to-day system checkouts practical, identifying minor, and perhaps otherwise overlooked, adjustment problems.

4.0 CONCLUSIONS

The subsonic choked-flow laser velocimeter calibrator/velocity standard developed has met the established requirements. The analysis demonstrated, a standard deviation in Mach number of 0.2 percent or less can be obtained, a flow angle deviation of 0.1 deg or less can be attained, probe position error insensitivity, good optical access, and low background laser light levels. Also, characteristic of the device is: immunity to external conditions; no required periodic calibration; low maintenance required; operation from available shop air supply, remote operation capability; and compact size.

These properties enable the use of the device for resolving the dilemma of the "startup drift" and a limited amount of beam cross plane angle calibration.

4.1 RECOMMENDATIONS

In order to be able to routinely check beam-cross-plane angles, in the majority of cases, and to check the angle between the beams, it is recommended that a small development effort continue in order to mount the choked flow nozzle on a precision rotation mount (so the flow angle can be adjusted) and to characterize the absolute velocity and absolute angle of the flow.

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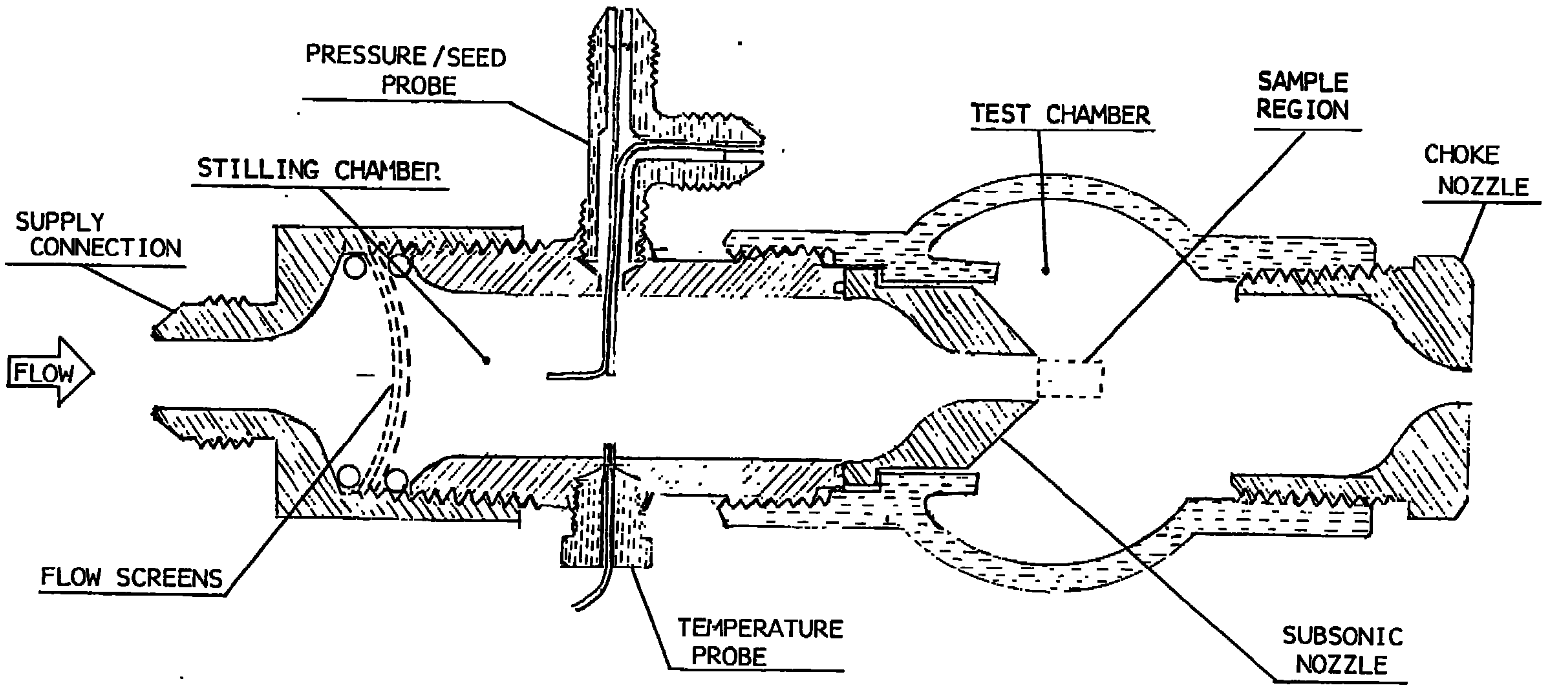

Figure 1. Choked-Flow Subsonic Nozzle

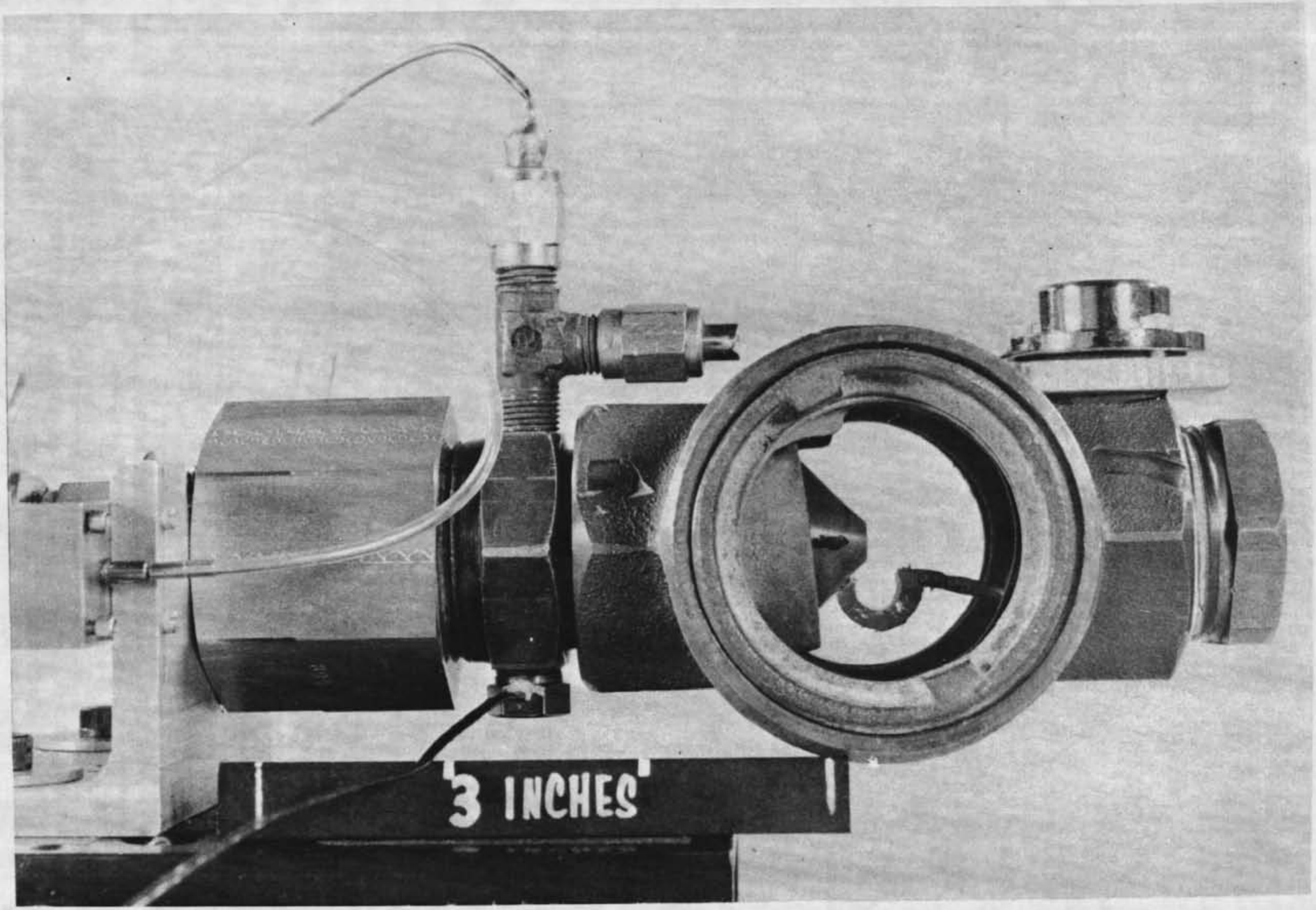

Figure 2. Choked-Flow Subsonic Nozzle LDV Calibrator/Velocity Standard

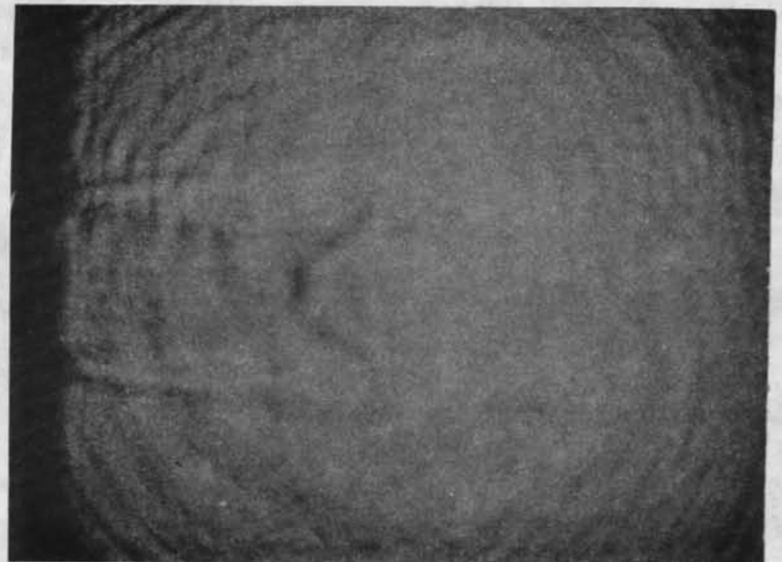

Figure 3. Choke Nozzle Exhaust Shadowgraph - Supply = 60 psi

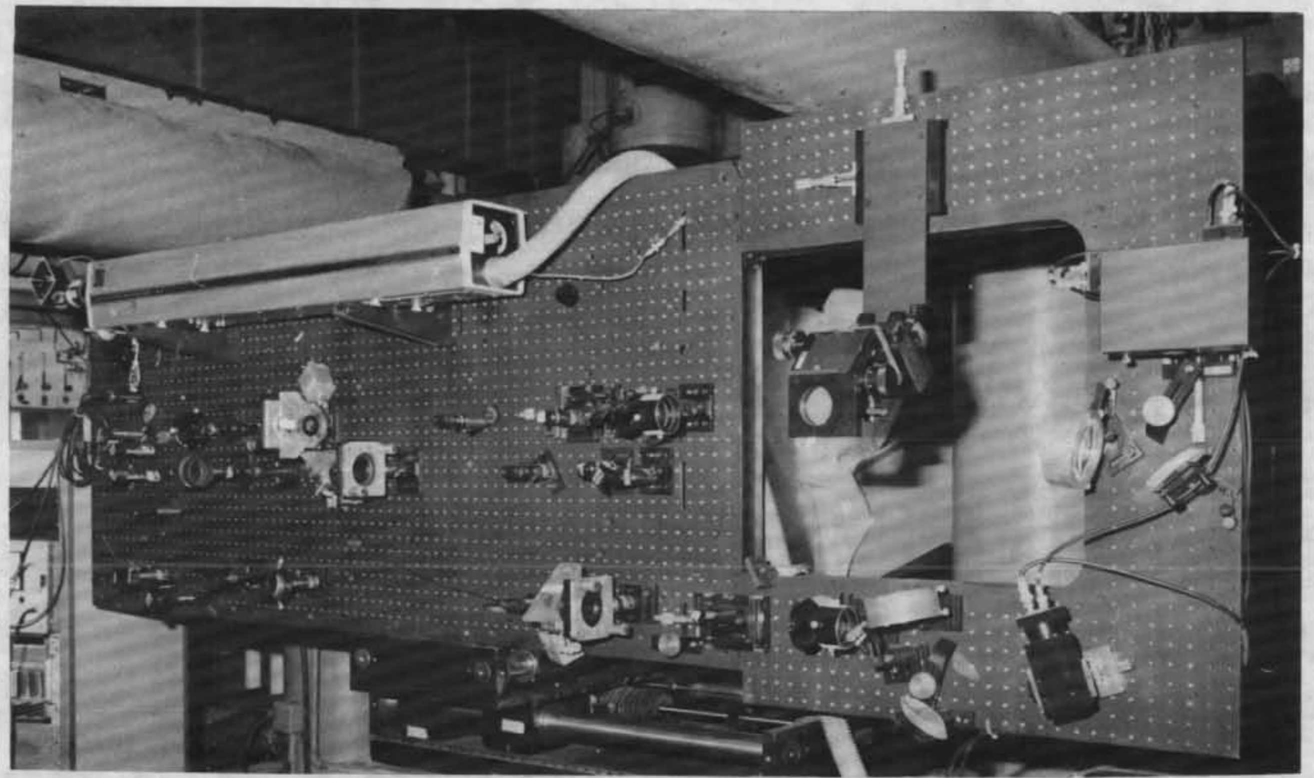

Figure 4. Three-Component Laser Doppler Velocimeter

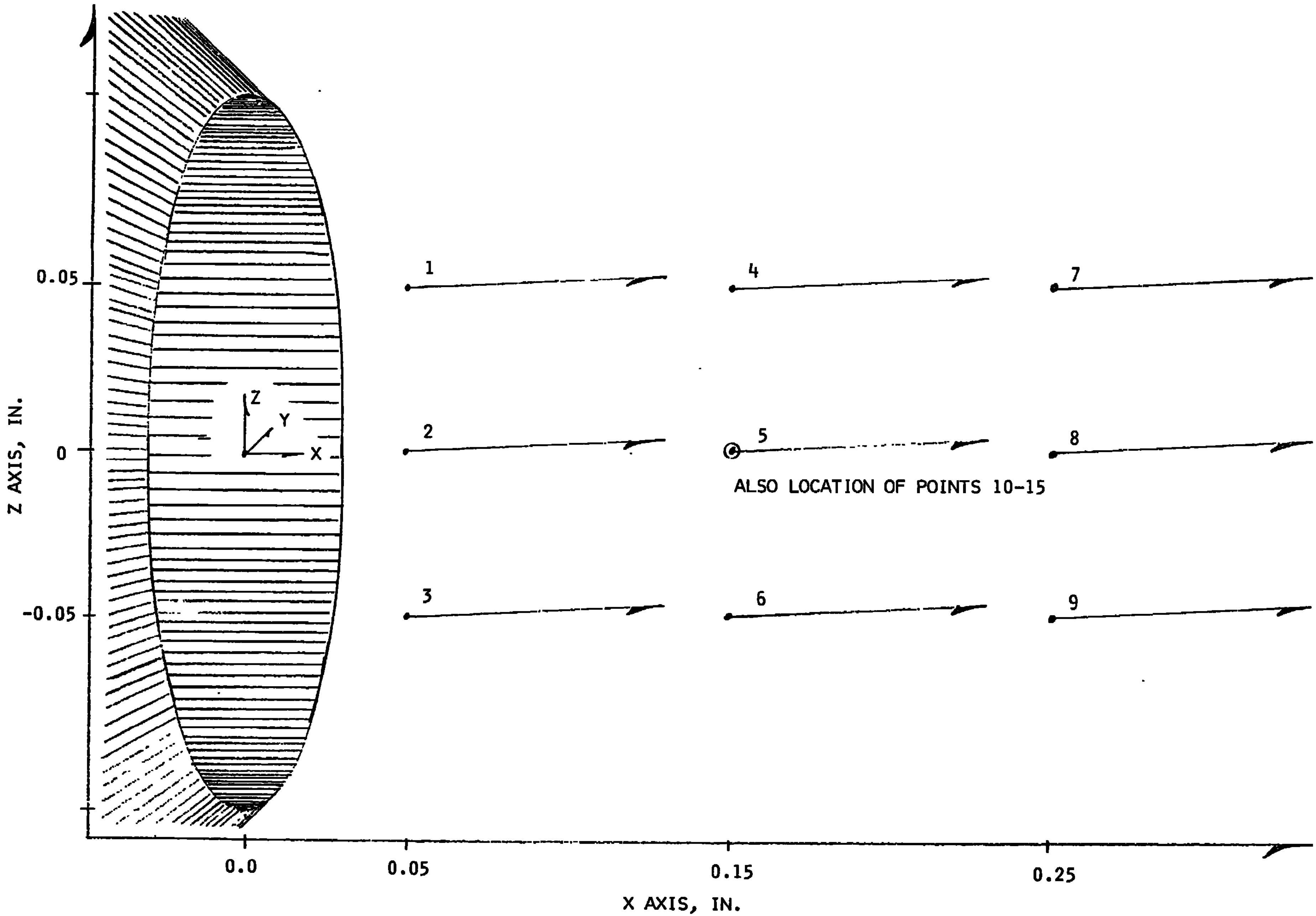

Figure 5. Subsonic Nozzle LDV Measurement Locations with Velocity Vectors

Table 1

Subsonic Nozzle LDV Data and Calculated Parameters

SEQUENCE NO.	POSITION INCHES X	Y	Z	NOZZLE SUPPLY CONDITIONS T,°F	P,psig	VELOCITY MAGNITUDE fps	FLOW ANGLE deg	MACH NUMBER	PERCENT DEVIATION IN MACH NUMBER (FROM AVG OF 1-9)
1	0.050	0.0	0.05	72.0	30.0	514.4	2.43	0.4653	+0.17
2	0.050	0.0	0.00	72.0	30.0	514.7	3.11	0.4656	+0.23
3	0.050	0.0	-0.05	72.0	30.0	513.4	3.01	0.4644	-0.02
4	0.150	0.0	0.05	72.0	30.0	514.2	2.52	0.4651	+0.13
5	0.150	0.0	0.00	72.0	30.0	513.3	3.22	0.4643	-0.05
6	0.150	0.0	-0.05	72.0	30.0	513.2	3.11	0.4642	-0.07
7	0.250	0.0	0.05	72.5	29.8	513.2	2.58	0.4640	-0.11
8	0.250	0.0	0.00	72.5	29.8	513.2	3.32	0.4646	-0.11
9	0.250	0.0	-0.05	72.5	29.8	512.9	3.15	0.4637	-0.17
10	0.150	0.0	0.00	72.0	30.2	513.0	3.25	0.4641	-0.09
11	0.150	0.0	0.00	72.0	25.1	512.3	3.19	0.4634	-0.24
12	0.150	0.0	0.00	73.0	20.0	511.8	3.28	0.4625	-0.43
13	0.150	0.0	0.00	114.0	30.0	537.1	3.30	0.4677	+0.69
14	0.150	0.0	0.00	116.5	25.0	537.8	3.28	0.4673	+0.60
15	0.150	0.0	0.00	118.0	19.6	539.2	3.27	0.4679	+0.73